Dexterous Telemanipulation with Four Fingered Hand System

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Summary

The paper briefly describes (he semi anthropomorphic telemanipulation system and discusses the advanced capabilities that were demonstrated in the initial performance evaluation. The system's terminus devices are anthropomorphic: an exoskeleton sixteen degree of freedom (DOF) glove controller that senses human finger forces and backdrives slave motions to every joint of its four instrumented fingers; and a four fingered sixteen DOF anthropomorphic slave hand- wrist-forearm. The master glove is attached to a non-anthropomorphic six DOF universalforce-reelecting hand controller (FRHC). The mechanical forearm is mounted to an industrial robot (PUMA 560), replacing its standard forearm. Active electromechanical compliance (AEC) systems for each finger and the wrist provide adjustable compliance, enabling human-like soft grasping. The system is controlled by a high performance distributed control system. Initial performance evaluations focussed on tool handling capabilities and astronaut equivalent task executions. Results reveal that the combination of a fingered hand and active compliance enables unprecedented task executions. But it also became evident that complex manipulations require a dual arm robot.

Introduction

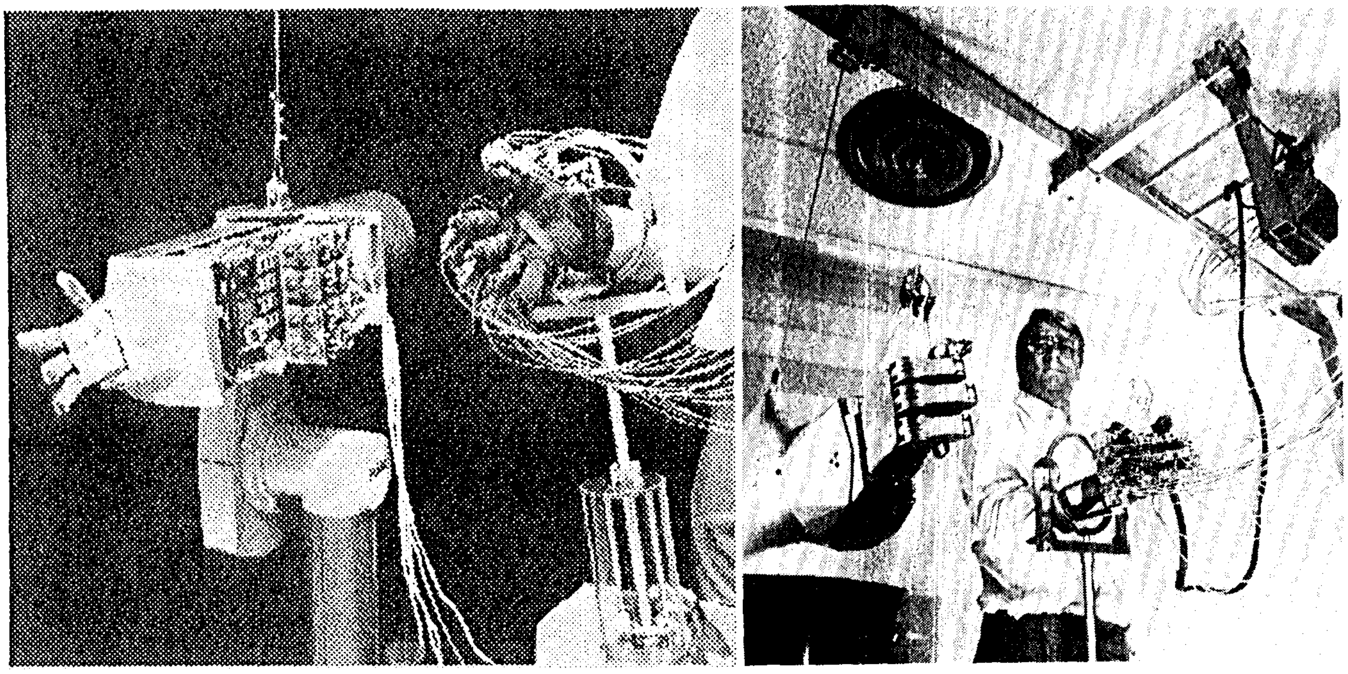
A human hand can manipulate a large variety of tools and equipment, This enables task executions that cannot be done bare-handed. A multifunctional robot needs tool handling skills too, enabling it to execute a variety of general purpose tasks that cannot be done by the robot hand alone. It elevates the robot's skills beyond guiding special purpose equipment or pick-and-place operations. Endowing the robot with manipulation capabilities requires special features, among them a fingered hand, Other important criteria will be listed in the performance evaluation section. The purpose of this research is to develop such a multifunctional, general purpose telerobotic system and ready it for a variety of applications such as space, the nuclear industry and other terrestrial applications. A new application for the motorized glove emerges in the medical field: The glove can be used as a rehabilitation physical therapy aid for helping patient's recovery from hand injuries or for rehabilitating grasp and fine movement control in stroke patient's paralytic hand. The system was evaluated primarily with astronaut space walk tools [1] in an effort to determine how well this telerobot can perform compared to the astronaut's gloved hand.

This system separates itself from other fingered mechanical hands [2,3] primarily through the following items: The all electric.al drive system which is required for space use, the true anthropomorphic design and kinematics of its forearm, enabling direct human inputs, the self-contained forearm, housing all drive units, the adjustable compliance system and the backdrivable glove controller.

System description

The telemanipulation system is shown in Figs. 1 and 2. It consists of a master controller, a manipulator arm and the control electronics (not visible in these pictures). The master' arm/glove and the slave arm/hand have 22 active joints each. The manipulator arm has five additional drives that control individual finger and wrist compliances.

Master controller: The master controller is comprised of the FRHC [4], controlling the robot arm and the glove controller which controls the robot hand. The FRHC controls the robot's wrist in either position/orientation or force control and provides equivalent feedbacks to the operator. The universal FRHC is cinematically dissimilar to the robot, it is universal and can be used for any robot arm having not more than six DOF. The telescoping part of the FRHC is gravity compensated so that the operator does not feel any gravitational effects from the master controller. Operational space at the wrist is a 45 cm cube working area. Interactions between master controller and human operator take place solely through the glove structure which is firmly attached to the last joint of the FRHC.



Figs. 1,2: The Semi Anthropomorphic Telemanipulation System

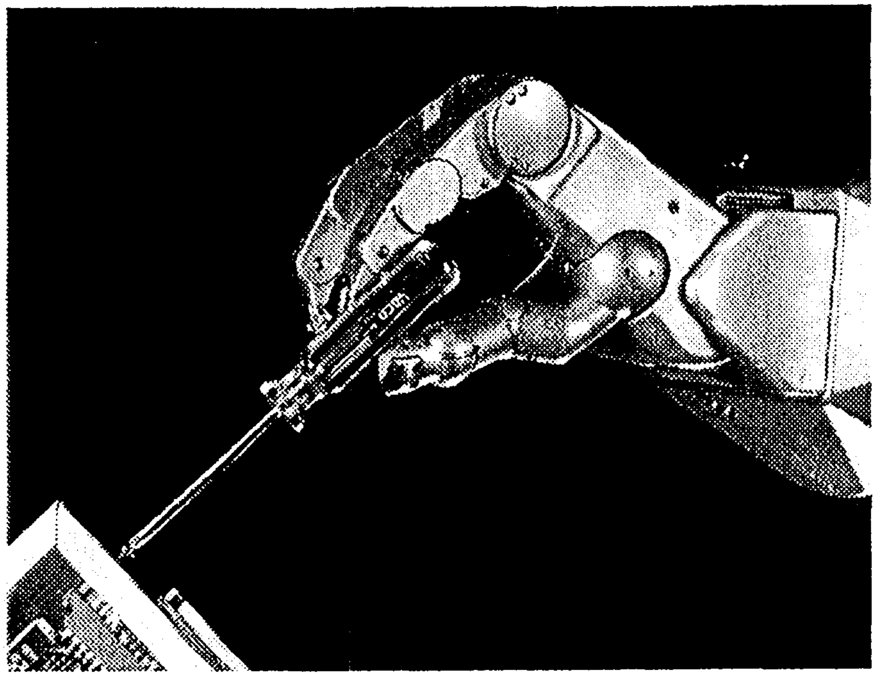
The glow controller [5] is worn by the operator. Its force *sensors* enable hybrid position/force and compliance control of the mechanical hand. Four fingers are instrumented, each having four DOF. Position feedback from the mechanical hand to each of the 16 finger joints provides the operator with a sense of operating on location. The feedback actuators are remotely located and linked to the glove through flex cables. A one-to-one kinematic mapping exists between master glove and slave joints, thus reducing the computational efforts and control complexity of the hand subsystem. The exceptions to the direct mapping are the two thumb base joints which need kinematic transformations.

Manipulator arm: The manipulator arm consists of a PUMA 560 robot which had its forearm replaced by the anthropomorphic forearm assembly. The forearm weighs approximately 50kg. A cable links the forearm to an overhead gravity balance suspension system, relieving the PUMA upper arm of this weight. The forearm has two sections, a rectangular and a cylindrical. The cylindrical section, extending beyond the elbow joint, contains the wrist actuation system and also acts as a counterbalance to the forearm. The wrist's angular displacement capabilities are similar to the human wrist. The rectangular cross section houses all finger actuators, all sensors and the local control and computational electronics. The slave. hand, wrist and forearm form a mechanically closed system, that is, the hand cannot be used without its wrist.

The mechanical hand has four fingers with four DOF at each finger (Fig. 3). Finger thicknesses and configurations are comparable to a large male hand. The palm's thickness increases in size toward the wrist. Angular displacements at each finger joint are similar to the corresponding human joints. The hand is almost completely enclosed, preventing object intrusions that could jam its mechanism. All finger joints are linked to the actuating system through flex cables. The hand's kinematics is similar to the human hand, enabling tool manipulations and direct human control through the glove. A more detailed description of the hand can be found in publication [5].

Each finger and the wrist is linked to its own AEC system located in the forearm. The AEC system provides the muscle-equivalent secondary function (the primary function is position control), which is stiffness control. Controlled yielding at fingers and wrist enables human-like. soft grasping and other capabilities, for instance contour following, which is useful when cutting with a knife or guiding a wrench around the circular path around the screw axis. Besides compliance control, AEC enables automatic hybrid position/force control: The system automatically switches to the force control mode if an externally induced compliance deflection is sensed.

Control electronics: The control electronics for the master glove and the anthropomorphic hand/wrist is PC based. Daughter boards (one each for master and slave)



Fig, 3: The Anthropomorphic Hand

contain a TMS320C40 (C40) processor, TI modules and other hardware to handle the digital control. The boards also provide the means for communicating to a supervisory program on the PC. All programs arc written in C. The SPOX Real-Time Operating System (Spectrum Microsystems) was used to facilitate the development of multi-process programs. The C40S communicate with each other via a single, duplex communication channel. This link will be the connection between the control station and the remote worksite which, in the future, might be a satellite communication link. The interface to the FRHC and the PUMA upper arm joints is provided by two separate Universal Motor Controllers (UMC's) [6].

The computing architecture was custom developed for this system and is described in [7]. It supports several distinct functions: filtration of sensed signals, control law implementation, modeling of voltage-velocity curves for motor control and inverse kinematics,

Two intelligent controllers (Fig. 4), based on Texas Instrument TMS320C30 (C30), arc placed near the system's sensors, onc is near the master glove, the other located inside the slave's forearm. The function of the controllers arc to sample analog signals, to filter those signals, to generate PWM signals, to provide the calibration of the strain gages (master only), to model the actuator's voltage-velocity curves, and to commtrnicatc with the PC based computational engine.

Sensor signals arc sampled at 2kHz using 12bit, 8 channel A/D converters (MAXIM 180). All strain gage signals are amplified by digitally-calibrated signal stage OP-AMP circuits. The motors are driven by a custom dc.signed PWM circuit, composed of a Dual Ported Memory and several PALs (Programmable Array Logic). The circuit generates the 16 PWM signals needed to backdrive the exoskeleton glove and the 20 signals needed to drive the anthropomorphic hand, including the four compliance drives (one per finger), and 4 PWM signals for the three DOF wrist and its compliance control, In addition, the controller monitors joint and force limits and can stop the system if preset limits arc exceeded. The amplifier drive circuits, based on the National Semiconductor 18201 H-Bridge (PWM amplifier), provides power signals to the motor.

The C30 uscs a UART (Universal Asynchronous Receiver/Transmitter) to provide an RS-232 serial line communication to the PC. The RS-232 serial interface between the Intelligent Controller and the PC is used to download programs. Sensor data and actuator commands arc communicated to the computational engine via a custom built 4MHz synchronous serial interface that runs between the C30 and onc of the six parallel communication ports of the C40.

A monitor program was written for the C30 and resides in the EPROM. This program boots the computer, pro-

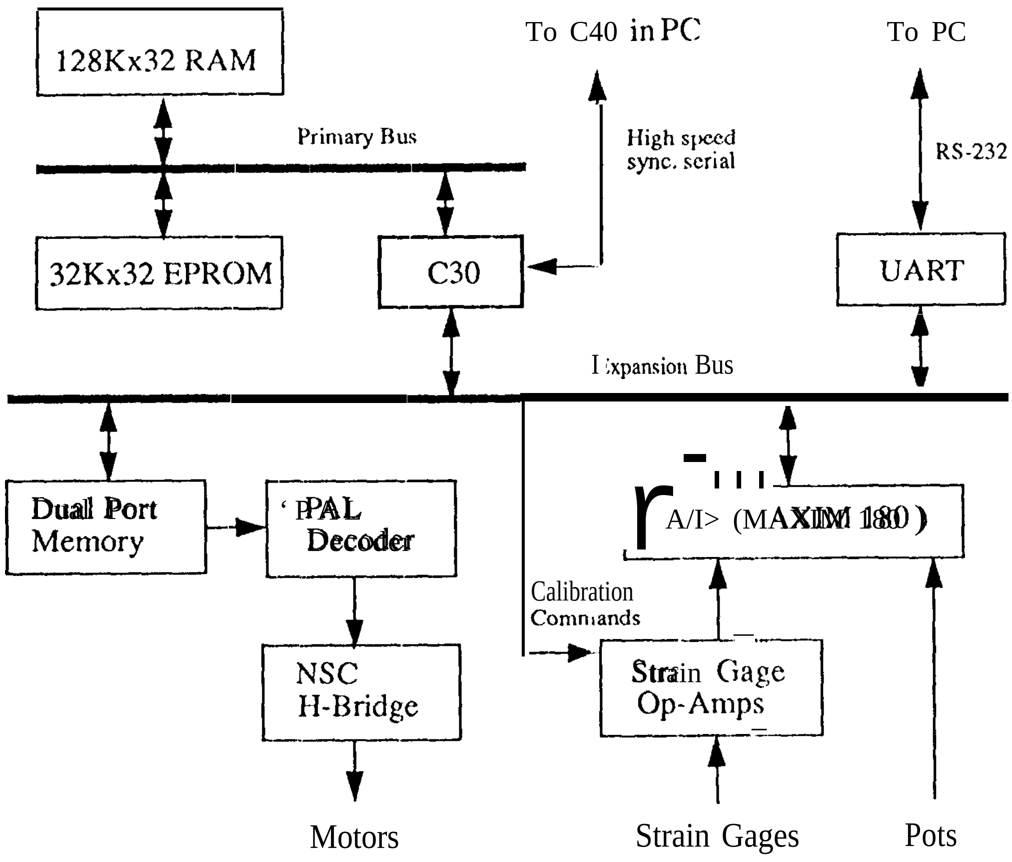


Fig. 4: Schematic of Intelligent Controller

vides functions such as memory test, calibration and program downloading, Programs are downloaded via the RS-232 into the RAM memory.

Performance evaluation

A study [8] preceded actual robot testing, analyzing the feasibility of handling all currently available extra vehicular activity (EVA) astronaut tools by a general purpose, dexterous robot. It revealed that out of the 195 eligible EVA items, 171 could be operated by dual anthropomorphic robot arms. A one handed anthropomorphic robot could handle 29 items whereas a robot with a common end effector could handle only six EVA tools. Not considered in the above numbers is the mandatory tethering which is required for all space operations. Engaging a safety tether (lock-leek type) always requires two hands, even for the astronaut.

Initial performance testing focussed on evaluating the. robot's astronaut tool handling capability. Of the 29 eligible astronaut tools, ten were. selected for testing based on how easy it was to reproduce such EVA-alike tools. Those ten items are: connector demate tool, force measurement scale, hydrazine brush, loop pin extractor, probe, ratchet, handheld socket, EVA switch, tether, and allen wrench. The above items were successfully operated. Other challenging tasks that were successfully executed include: cutting with a knife, holding a hand crank and following its circular motion, handling an egg where this delicate object was completely embraced by the hand's grip, thus no clamping forces or soft finger padding was required, handling bulky objects with the open faced hand (these objects were too large to be clamped by common end effectors), picking up a soft cover book from a flat surface, picking up a certain computer diskette form a stack inside a box, operate a trigger while holding the power tool, and even cutting a sheet of paper with a scissor. These tasks reveal the robot's versatility and diversity.

The following paragraphs describe some of the demonstrated general handling skills. Quantitative results are not included because soon to be implemented system modifications (i.e. friction reductions will increase clamping strengths) would render such data meaningless within a short time.

Object grappling: Grasping objects with the hand in compliant mode simplifies the grappling process because compliance enables self-aiignmcnt of hand and fingers to the object, casing positional accuracy requirements during final approach and grappling. Compliance also' enables multi point object contact because individual fingers self-align to objects, resulting in a tight grip. The hand grasps objects primarily from onc side, allowing a much better view of the worksite than is possible with parallel jaw grippers. Also, less work space is required around objects which enables the hand to work in confined spaces.

Tool guidance: Tools that need to be guided along linear paths (i.e. knife) can be handled quite well due to the wrist's compliance. Tools requiring tightening motions around an axis (i.e. wrench) could also be operated: To tighten the screw, the wrench has to move around the screw axis in a circular path. Two key capabilities enable the tightening operation: 1) The hand's articulation enables to embrace the tool handle without using much clamping force. The lock-in grip of the hand allows relative motions between tool handle and hand without loosing the tool grip. 2) The compliant wrist can flex. Thus, the hand does not have to follow the curvilinear tool path accurately because relative motion and flexing keep the tool self-aligned to the screw during tightening. Not having to follow the tool path accurately, which is a hard task for teleoperated operations, simplifies this tool guidance considerably.

7001 *manipulations:* Hand tool manipulations with the robot hand arc surprisingly difficult to perform, even with the articulation this hand has. Some tool manipulation tasks were demonstrated, i.e. cutting with a scissor or engaging a simple tethering device. This task required to open onc locking device while holding the tether at the same time. The lack of tactile sensing was quite evident in tool manipulations: human tactile sensors not only sense the locations of contact but also the strengths and directions of the applied forces, thus enabling the human hand to exert proper reactive forces. This makes human tool manipulations easy. The lack of tactile sensing in the mechanical hand severely hampers tool manipulations.

Assembly tasks: The positional give-and-take capability enabled through the robot's compliance provides the needed slack to align mating objects with respect to each other. AEC is a breakthrough for assembly tasks in unstructured environments where the locations/orientations of mating parts arc not accurately known,

The following items arc important considerations in designing manipulation capable robots. Some capabilities arc desirable but not yet available or implemented in our robot.

Number of fingers needed: In order to securely hold and manipulate an object, a minimum of four fingers arc required: It takes at least two fingers opposite the thumb to rigidly hold the object in a stable grip. A fourth finger is needed to do the manipulation (i. c. squeeze a trigger or regrasp the object so that it can be properly aligned within the hand for subsequent manipulation tasks), Experiments proved that three fingers could not perform manipulation tasks because tool handles kept pivoting around the two grasping fingers, moving the manipulation device (i.e. trigger) away from the finger that was intended to do the manipulation.

Why dual anthropomorphic arms are needed: Mosl tool manipulations require. two hands to simplify the task, i.e. holding a pliers near its hinging point with onc hand while operating it with the other. This subdivides the manipulation task into two simpler operations: tool holding and tool actuation. Many tasks require a second hand to hold the equipment: The scissor task needed a second hand to hold the paper, wire cutting with a pliers requires another hand to hold the wire. The EVA evaluation further illustrates the need for dual hands: only 29 out of the 195 EVA tools could be handled with a single hand. This does not include the mandatory tethering operation required for space operations which requires two hands anyway.

An often overlooked fact is that a tool must first be grabbed and then oriented to place the tool handles properly into the hand. It also might be necessary to take tools out of stowage caddies or pull them from holders, snap-on clamps or velcro, Our experimentation showed that placing tool handles correctly into the robot hand (i.e. the loops of a scissor need to be placed over the fingers) requires the assistance of a second hand.

Prerequisites for dual arm manipulations: 1) Redundant seven DOF arms arc needed to reach around obstructions, to properly align the arms w.r.t. each other and to avoid arm interferences. 2) Arm compliance is needed for cooperative dual arm manipulations of rigid objects.

Criteria that will enhance robot manipulation capabilities: The following list, based primarily on our experimentat ion, states the seven most important criteria that will advance the state of the art of dexterous robot manipulation capabilities: 1) A fingered hand for, as with humans, most tool manipulations require individual finger motion capabilities. 2) Active human-like compliance, for instance to self-align the hand to an object, thus reducing control complexity. 3) A true anthropomorphic hand configuration, enabling direct hand motion simulations by a human operator (efficient autonomous control of fingered hands is still years away). 4) An effective hand (glove) controller with feedback: Experimentation with the glove's position feedback turned off revealed that it is almost impossible to control the hand without receiving positional feedback information. 5) State of the art electronics control and an effective data display system to supervise the complex dexterous system (our system currently has 49 DOF). 6) Tactile sensing: A human relies more on touch than on vision once contact with an object is established. This became evident during our manipulation endeavors which were hampered by the lack of tactile feedback, It caused slowdowns in operational speeds and a strong reliance on visual feedbacks. Research in how to implement tactile feedback in a multi fingered hand and how to provide the information to the operator is needed. 7) Good visual feedback.

Conclusions, future work

Performance evaluations revealed the robot's capabilities for multifunctional operations, including tool handling and manipulation skills. Hand tool experimentations proved that by utilizing hand tools, the robot's capabilities include numerous tasks that a common robot cannot do. It will open the way for countless new robotics applications. Most hand tool manipulations and all EVA tasks require a dual anthropomorphic arm system having at least four fingers per hand, active compliance and 7 DOF, compliant arms.

FY '95 development plans called for the implementation of major improvements that would substantially enhance the robot's skills. An upper arm, having its own independent compliance system needs to be built to create a seven DOF, fully anthropomorphic slave arm. A previously built seven DOF exoskeleton arm controller [9] is available to control the expanded 7 DOF robot arm. A second, non-anthropomorphic master/slave system is already in our lab for experimentations with a mixed anthropomorphic/non-anthropomorphic dual arm system.

Unfortunately, NASA/JPL's priorities have shifted toward robotic Mars exploration which, duc to mass limitations and signal time delays to Mars, exclude our telemanipulation system. Regretfully, support for this work has therefore been reduces that a continuation of this work now depends on securing other funding sources which are still pending,

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